Top-Down Models and Extremely High Energy Cosmic Rays

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Abstract

We developed numerical code for calculation of the extragalactic component of the spectra of leptons, nucleons and γ-rays resulting from "top-down" (non-acceleration) models for the case of uniform and isotropic source distribution. We explored two different classes of "top-down" scenarios: the wide earlier investigated class of X particles coming from collapse and/or annihilation of cosmic topological defects (such as cosmic strings, monopoles, etc.) and the models of super-heavy long-living X particles with lifetime of the order or much greater than the current Universe age.

I. INTRODUCTION

The ultra-high energy cosmic ray (UHECR) events observed above 10^{20} eV [1,2] are difficult to explain within conventional models involving first order Fermi acceleration of charged particles at astrophysical shocks [3]. It is hard to accelerate protons and heavy nuclei up to such energies even in the most powerful astrophysical objects [4] such as radio galaxies and active galactic nuclei. Nucleons of the energies above $\simeq 4 \times 10^{19}$ eV are strongly decelerated due to photo-pion production on the cosmic microwave background (CMB) — the Greisen-Zatsepin-Kuzmin (GZK) effect [5] — on the distances less than $\simeq 100$ Mpc [6]. Ultra high energy electrons lose their energy even faster due to synchrotron radiation in galactic as well as extragalactic magnetic field. Heavy nuclei are photodisintegrated in the CMB within a few Mpc [7]. There are no evident astronomical sources of UHECR within $\simeq 100$ Mpc of the Earth in the frame of conventional acceleration models.

To avoid these difficulties one may assume that UHECR are created directly at energies comparable to or exceeding the observed ones rather than being accelerated from lower energies. In these so-called "top-down" scenarios γ-rays, leptons and nucleons are initially produced at ultra-high energies by the decays of supermassive particles generically called X-particles. The sources of X-particles could be topological defects (TD) such as cosmic strings or magnetic monopoles that could be produced in the early Universe during symmetry-breaking phase transitions envisaged in Grand Unified Theories. In the inflationary Universe, the relevant TD could be formed in a phase transition at the end of inflation. Another possibility is to produce super-heavy long-living particles thermally during reheating epoch of the Universe [8] or from vacuum fluctuations during inflation [9].

There were several papers dedicated to the calculation of the observable spectra of UHECR [10,13,14]. The most detailed discussion of propagation of nucleons, photons and electrons is given in ref. [10]. It has, however, some drawbacks which we discuss below. We have developed an independent numerical code for calculation of the extragalactic component of the spectra of leptons, nucleons and γ-rays resulting from an X-particle decays in the top-down models of UHECR, for the case of uniform and isotropic source distribution. Our general strategy is similar to that of ref. [10], but we use another numerical scheme for the solution of transport equations, and take into account process of proton-photon scattering $p\gamma_b \to p\gamma$ disregarded previously.

In this paper we present the results of numerical calculations of the observable spectra in two top-down models. The first one belongs to the class of models examined in [10], and we use it for testing our code. The second model is based on the decays of superheavy relic particles; it was not considered in ref. [10] We shall discuss the differences in the observable spectra predicted in different models, and derive constraint on X-particle lifetime in the second model.

II. INJECTION SPECTRA AND EVOLUTION

The generic top-down mechanism of production of UHECR looks as follows: the X-particles with typical GUT masses m_X of the order of $10^{14} - 10^{16}$ GeV decay into leptons and quarks. The strongly interacting quarks fragment into jets of hadrons resulting in mesons and baryons. Mesons, in turn, decay into photons, electrons and neutrino. Together with baryons these particles form the primary injection spectrum.

Injection spectrum for a given particle species (a) from the hadronic channel can be written as

$$\Phi_a(E, t) = \frac{dn_{d,X}(t)}{dt} \frac{n_q + n_e}{m_X} \frac{dN_a(x)}{dx} , \qquad (1)$$

where $x \equiv E(n_q + n_e)/m_X$, and dN_a/dx is the effective fragmentation function describing the production of the particles of species (a) by the original quark. The *total* hadronic fragmentation spectrum dN_h/dx in the energy range of our interest is not yet known definitely. Some possibilities were described in ref. [13]. In our current calculations we have used the following fragmentation function,

$$\frac{dN_h(x)}{dx} = \begin{cases} \frac{15}{16}x^{-1.5}(1-x)^2 & \text{if } x_0 \le x \le 1 \\ 0 & \text{otherwise} \end{cases} , \qquad (2)$$

where the value x_0 corresponds to a cut-off energy $\sim 1\,\text{GeV}$. Equation (2) is one of the simplest QCD-motivated forms of hadronic fragmentation spectrum [15]. Assuming a nucleon content of $\simeq 3\%$ and the rest equally distributed among the three types of pions, we can write the fragmentation spectra as [20,21]

$$\frac{dN_N(x)}{dx} = (0.03) \frac{dN_h(x)}{dx} , \qquad (3)$$
$$\frac{dN_{\pi^+}}{dx} = \frac{dN_{\pi^-}}{dx} = \frac{dN_{\pi^0}}{dx} = \left(\frac{0.97}{3}\right) \frac{dN_h(x)}{dx} .$$

From the pion injection spectra one gets the resulting contribution to the injection spectra for γ-rays, electrons and neutrinos.

Consider now the dependence of the decay rate of X-particles on time. In a wide class of models involving topological defects the rate of production (and, therefore, the rate of decay) of X-particles can be parameterized as

$$\frac{dn_X}{dt} \propto t^{-4+p}, \tag{4}$$

where the index $p \geq 0$ depends on the nature of topological defects from which X-particles are produced. For example, production of X-particles by a network of ordinary cosmic strings in the scaling regime would correspond to $p = 1$ if one assumes that a constant fraction of the total energy of closed loops goes into X-particles [11,12]. Models based on annihilation of magnetic monopoles and antimonopoles [15,16] predict $p = 1$ in the matter dominated and $p = 3/2$ in the radiation dominated era [17] whereas simplest models involving superconducting cosmic strings lead to $p = 0$ [18]. A constant comoving injection rate corresponds to $p = 2$ and $p = 5/2$ during the matter and radiation dominated era, respectively.

Another model that we will consider involves primordial X-particles with the mass of order 10^{22} eV and the lifetime of the order of the age of the Universe or greater. These particles may be produced thermally during reheating epoch [8] or from vacuum fluctuations during inflation [9] and may constitute a considerable fraction of Cold Dark Matter (CDM). X particle density in this model is

$$n_X(t) = n_i \frac{(1+z)^3}{(1+z_i)^3} e^{-\frac{t-t_i}{\tau_X}}, \tag{5}$$

where n_i is X-particle density at some arbitrary initial moment $t_{i,X}$, z is the redshift corresponding to time t, $z_{i,X}$ is the initial redshift, and 10^{10}years $\leq \tau_X \leq 10^{22}$years is X-particle lifetime. We normalize X-particle concentration by assuming that at $z_i \sim 100-1000$ (matter dominated phase) the density was approximately equal to the critical density at that time. Then we get

$$n_i = \frac{\rho_0}{m_X}(1+z_i)^3, \tag{6}$$

where ρ_0 is today's critical density. Taking into account that $t_i \ll t$ (the major contribution to the observable flux comes from $z \lesssim 10$) we obtain

$$n_X(t) \simeq \frac{\rho_0}{m_X}(1+z)^3 e^{-\frac{t}{\tau_X}}. \tag{7}$$

Finally, X particle decay rate reads

$$\frac{dn_{d,X}}{dt} \equiv (1+z)^3 \left| \frac{d}{dt}\left(\frac{n_X(t)}{(1+z)^3}\right) \right| = \frac{\rho_0}{m_X \tau_X}(1+z)^3 e^{-\frac{t}{\tau_X}}. \tag{8}$$

For the full determination of the injection spectra one needs also to specify the X-particle decay mode. In what follows we assume that X-particle decays on n_q quarks and n_e electrons and all these initial decay products share energy equally: $E_q = E_e = m_X/(n_q + n_e)$.

One remark concerning the model of primordial X-particles is in order. One has to take into account the fact that these particles are concentrated mostly in galaxies, and so the electron component of injection spectra is heavily suppressed due to synchrotron radiation in the galactic magnetic field. For the same reason there is an additional contribution in photon spectrum. In the case of the decay mode $X \to n_q q$ typical electron energy is $10^{19} - 10^{20}$ eV for $m_X = 10^{22}$ eV and $n_q = 2, 3$. In the galactic magnetic field of strength $B \simeq 10^{-6}$G the energy of the synchrotron photons produced by such electrons is about $10^{14} - 10^{15}$eV. Photon attenuation length at those energies is extremely small due to pair production on microwave background, so one should expect that the synchrotron component is also negligible. In the present paper we approximate this effect by simply excluding electrons from the injection spectra. It is worth noting that the contribution of our Galaxy to the observable flux may be non-negligible. In this paper we present calculation of the extragalactic component of the observable flux only. The calculation of the Galactic contribution requires separate detailed calculation [19].

III. INTERACTIONS OF ELECTRONS, PHOTONS AND NUCLEONS WITH BACKGROUND RADIATION AND EXTRAGALACTIC MAGNETIC FIELD

The γ-rays and electrons produced by X particle decay initiate electromagnetic (EM) cascades on low energy radiation fields such as the cosmic microwave background (CMB). In the absence of magnetic field EM cascades are driven mostly by the cycle of pair production (PP; $\gamma\gamma_b \to e^- e^+$) and inverse Compton scattering (ICS; $e\gamma_b \to e'\gamma$). The energy degradation of the "leading" particle in this cycle is slow. Other EM interactions that influence the γ-ray spectrum in the energy range of interest are triplet pair production ($e\gamma_b \to ee^- e^+$) and double pair production ($\gamma\gamma_b \to e^- e^+ e^- e^+$), as well as synchrotron losses of electrons in the large scale extragalactic magnetic field (EGMF).

The relevant nucleon interactions implemented in the code are pair production by protons ($p\gamma_b \to pe^- e^+$), photoproduction of single or multiple pions ($N\gamma_b \to N\ n\pi$, $n \geq 1$) and neutron decay. Production of secondary γ-rays, electrons, and neutrinos by pion decay is in general negligible in the scenarios where injection is dominated by γ-rays and leptons over nucleons. Apart from these processes described in detail in ref. [10], for protons of energies $10^{15} - 10^{17}$ eV the inverse Compton scattering must be taken into account. Its cross section is identical to that for electrons (with the replacement of m_e by m_p).

There are two major uncertainties in the parameters which influence the particle transport. The first one concerns the intensity and spectrum of URB for which there exists only an estimate above a few MHz frequency [22]. We adopt the so-called "minimal" URB estimate that has a low-frequency cutoff at 2 MHz [22]. The other uncertainty is the mean value of EGMF and its time evolution. Conventionally, concerning particle propagation, EGMF is assumed to be constant and lying in the range $10^{-12}G \lesssim B \lesssim 10^{-9}G$ [10,13]. The other possibility is to assume that the total energy of EGMF is constant; this implies $B \sim (1 + z)^{3/2}$.

We assume a flat Universe with no cosmological constant, and a Hubble constant of $h_0 = 0.75$ in units of 100 km sec^{-1}Mpc^{-1} throughout.

IV. SOLUTION OF THE TRANSPORT EQUATIONS

An example of the transport equation for electrons which includes for simplicity only pair production (PP) and inverse Compton scattering (ICS) looks as follows:

$$\frac{d}{dt}N_e(E_e,t) = -N_e(E_e,t)\int d\epsilon\, n(\epsilon)\int d\mu \frac{1-\beta_e\mu}{2}\sigma_{\mathrm{ICS}}(E_e,\epsilon,\mu) + \tag{9}$$

$$\int dE_e' N_e(E_e',t)\int d\epsilon\, n(\epsilon)\int d\mu \frac{1-\beta_e'\mu}{2}\frac{d\sigma_{\mathrm{ICS}}}{dE_e}(E_e; E_e',\epsilon,\mu) +$$

$$\int dE_\gamma N_\gamma(E_\gamma,t)\int d\epsilon\, n(\epsilon)\int d\mu \frac{1-\mu}{2}\frac{d\sigma_{\mathrm{PP}}}{dE_e}(E_e; E_\gamma,\epsilon,\mu) + Q(E_e,t),$$

where $N_e(E_e,t)$ is the (differential) number density of electrons with energy E_e at time t, $n(\epsilon)$ is the number density of background photons of energy ϵ, $Q(E_e,t)$ is an external source term for electrons of energy E_e at time t, μ is the cosine of the interaction angle between the CR electron and the background photon ($\mu = -1$ for a head-on collision), and β_e is the velocity of the CR electron. The first term in (9) describes the loss of electrons due to ICS, the second one accounts for influx of electrons scattered into corresponding energy range due to ICS, and the third term describes the influx of electrons produced due to PP by photons. The processes with continuous energy loss $dE/dt = -f(E,t)$, such as synchrotron radiation, may be accounted for by including into the transport equations the additional term

$$\frac{dN}{dt} = ... + f(E,t)\frac{dN}{dE} \tag{10}$$

In order to solve the transport equations numerically, we divide each decade of energy into $n \sim 20$ equidistant logarithmic bins and define the central value of the i-th bin as E_i. Then we replace the continuous integrals by finite sums, and integrate Eq. (9) over one CR energy bin. The resulting set of differential equations has the form

$$\frac{d}{dt}N_a^i = -N_a^i\alpha_a^i + \sum_c\sum_j \beta_{ca}^{ij}N_c^j + Q_a^i. \tag{11}$$

where subscripts a and c refer to particle species. The coefficients α_a^i, β_{ca}^{ij} and Q_a^i depend on time and may be easily obtained from the original transport equation. For numerical solution of (11) we used the implicit scheme with Richardson extrapolation [23].

To account for redshifting S.Lee in ref. [10] performed the operation $N_a(E,z) \to [1 + \Delta z/(1+z)]^{-2}N_a\left(E[1 + \Delta z/(1 + z)], z\right)$ for each particle species a after a step Δz in redshift. Here Δz was matched conveniently with the logarithmic energy bin size, $\log_{10}[1 + \Delta z/(1 + z)] = \log_{10}(E_i/E_{i-1}) = 1/n$, which corresponds to the transformation $N_a^i(z) \to [1 + \Delta z/(1 + z)]^{-3}N_a^{i+1}(z)$.

It is important to note that the time interval Δt corresponding to Δz may be rather long. For example at $z \simeq 0$ and $n = 20$ one has $\Delta z = 0.12$, which corresponds to distances $\Delta l \simeq 360/h_0\mathrm{Mpc} \sim 500\,\mathrm{Mpc}$ and is much larger than the synchrotron loss length of electrons, $D \sim 1\mathrm{Mpc}$, at $E \sim 10^{23}\mathrm{eV}$ in the magnetic field $B = 10^{-11}G$. So, we have to divide time interval into smaller steps to account for all the fast processes such as synchrotron losses of electrons, GZK-cutoff for nucleons, etc. This was taken into account in the code.

V. RESULTS

In figs. 1-4 we present the results of our flux calculations. Since we have not taken into account the propagation through our Galaxy, the spectra presented refer to the fluxes of particles near the boundary of the Galaxy. Even in the absence of galactic sources, the observable flux of electrons will be smaller by several orders of magnitude at energies $E \gtrsim 10^{15}$eV, while the photon flux will contain additional component due to the synchrotron radiation in the galactic magnetic field [24].

We simulated the situation of fig. 14(a) in ref. [25] (see fig. 4). As a result we got the spectrum whose shape is mostly similar to fig. 14(a) in [25]. But there are some discrepancies in details which concerns especially the proton component and may in part be attributed to including elastic proton-photon scattering and also slightly different accounting for pair production by protons.

The fluxes of UHECRs in the model of long-living X-particles are proportional to τ^{-1}, which allows to impose constraints on X particle lifetime. For example, in the case of decay mode $X \to qq$ and $m_X = 10^{22}$eV, comparison of the levels of predicted spectra with the observed one leads to the constraint

$$\frac{\tau}{\Omega_X} \gtrsim 10^{10} t_0, \tag{12}$$

where t_0 is the today's age of the Universe and Ω_X is the relative density of X-particles at $z = z_i \sim 100 - 1000$.

The main difference in spectra resulting from TD and primordial X-particle models concerns the ratio of nucleon and electron-photon components at energies above 10^{18}eV. The reason is the absence of electrons in the effective injection spectra in the second model. We expect that this difference in spectra will persist even after including into consideration the galactic component of the UHECR.

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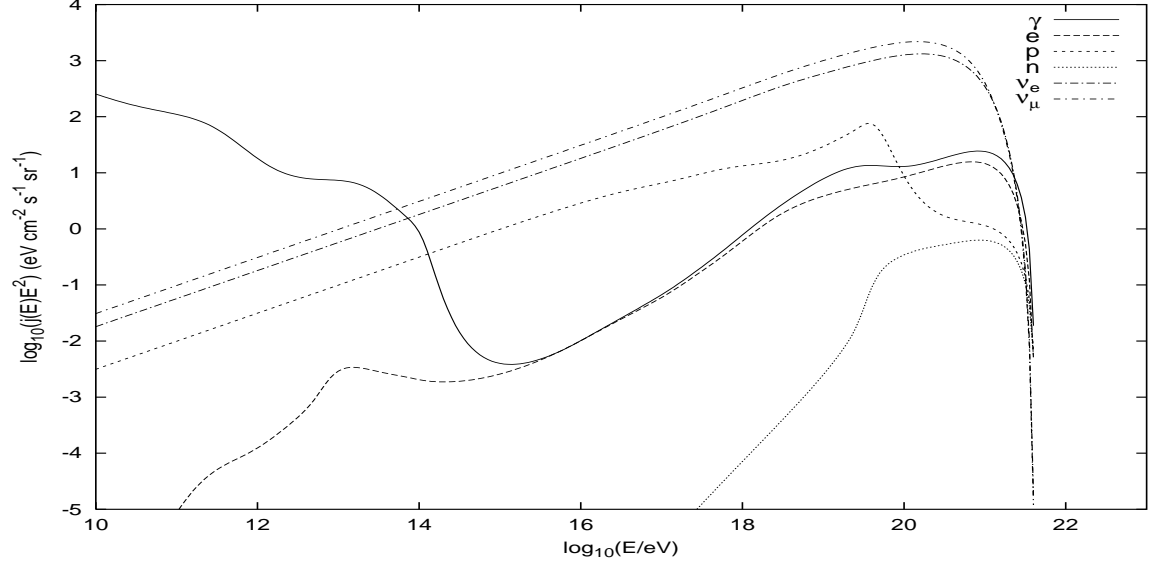
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FIG. 1. Extra-galactic component of the spectra in the model of long-living X-particles with $\tau = 10^9 t_0$ (t_0 is the age of Universe) and the decay mode $X \rightarrow qq$. The strength of EGMF is $B = 10^{-12}$G. Synchrotron losses in the Galaxy are not taken into account (see comments in Sect. V).
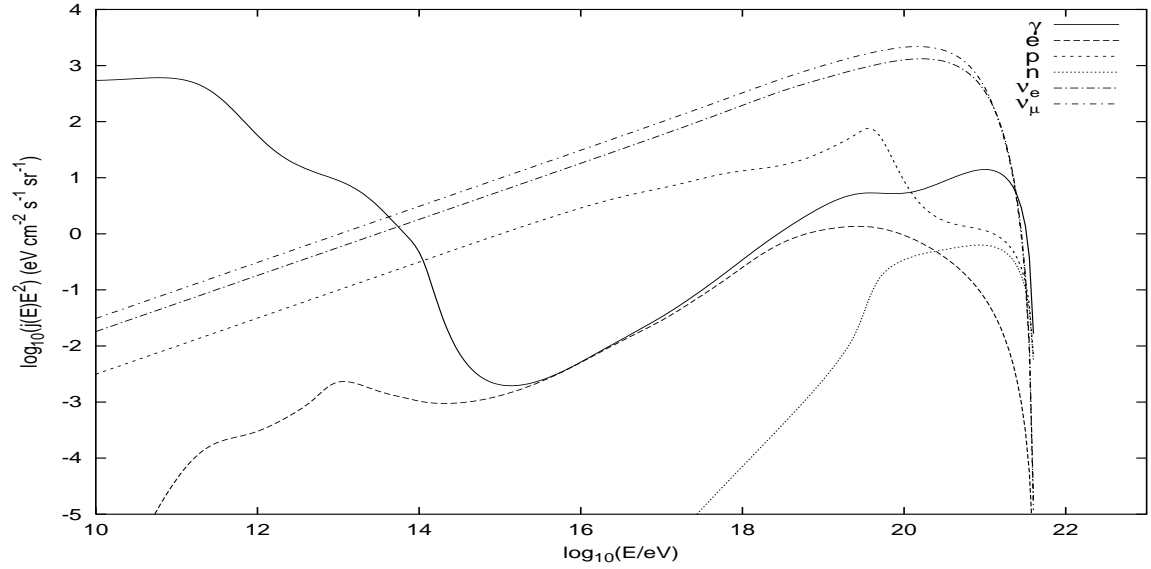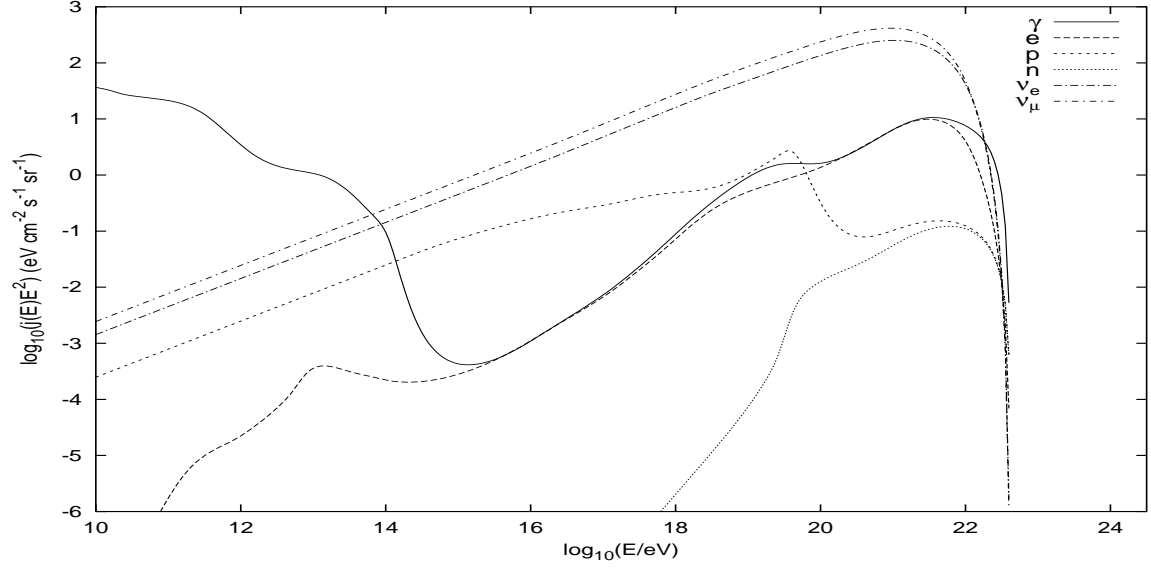

FIG. 2. Same as fig. 1 but for $B = 10^{-10}$G.

FIG. 3. UHECR spectra near the boundary of our Galaxy in the top-down model with $p = 1$, $M_X = 10^{23}$eV and constant EGMF $B = 10^{-12}$G, assuming decay mode $X \to qq$. The spectra are normalized to the observed flux at energy 10^{20}eV.

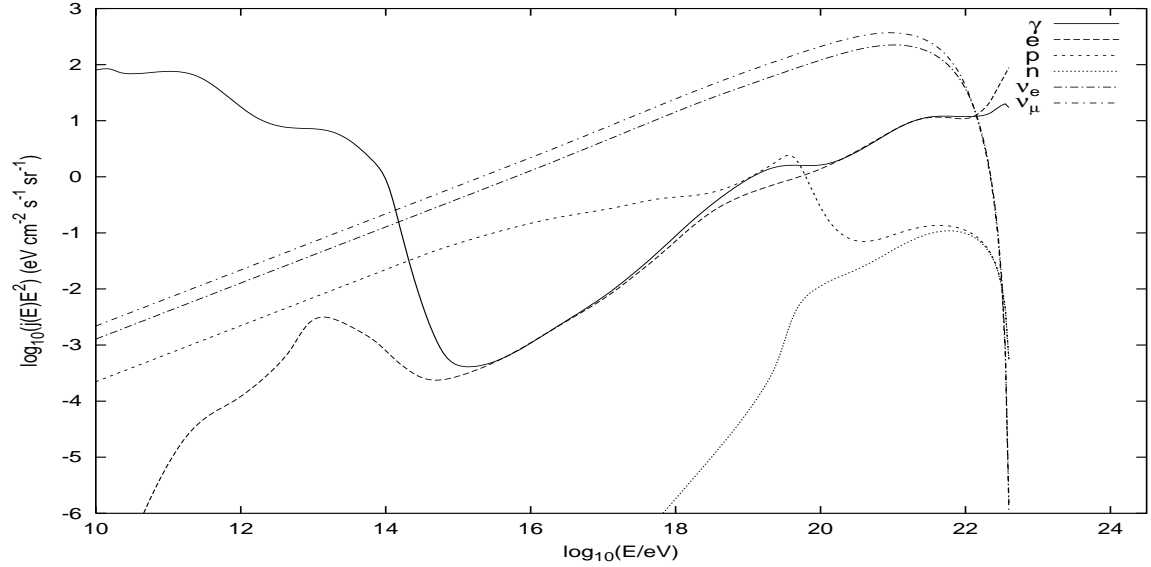FIG. 4. Same as fig. 3 but for the decay mode $X \to qe$.